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REPEATED-STRESS (FATIGUE) TESTING MACHINES USED IN THE MATERIALS TESTING LABORATORY OF THE UNIVERSITY OF ILLINOIS

BY

HERBERT F. MOORE

AND

GLEN N. KROUSE

CIRCULAR No. 23

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REPEATED-STRESS (FATIGUE) TESTING MACHINES USED IN THE MATERIALS TESTING LABORATORY OF THE UNIVERSITY OF ILLINOIS

I. Introduction

1. *Introductory.*—For some 15 years the problem of the failure of metals under repeated stress (commonly, but rather inaccurately, known as the "fatigue of metals") has been intensively studied at the Materials Testing Laboratory of the University of Illinois. During that time a number of special testing machines for studying of metals under repeated stress have been in use in that laboratory. These machines have been designed in the laboratory, and some have been built in the laboratory machine shop. It is believed that a description of some of them might be of service to other experimenters in their field. This circular makes no pretense of giving a description of every type of fatigue testing machine in use by testing engineers today.* Table 1 gives the capacity and the speed of operation of each machine described in this circular.

2. *Acknowledgments.*—A complete list of all persons who have given assistance in the design and construction of these machines would include the names of nearly every member of the staff of the department of Theoretical and Applied Mechanics for the past 15 years. Special acknowledgment should, however, be made to Messrs. M. K. Shafer and W. C. Boswell, mechanicians in connection with the various investigations of fatigue of metals, to Prof. H. R. Thomas, now engineer of tests with the Rails Investigation at the University of Illinois, to Mr. T. M. Jasper, formerly with the Fatigue of Metals Laboratory staff, now director of research with the A. O. Smith Corporation, to Prof. J. B. Kommers of the University of Wisconsin, and to Prof. W. J. Putnam of the University of Illinois.

This circular has been published as a part of the work of the Engineering Experiment Station at the University of Illinois, under the general administrative direction of Acting Dean A. C. Willard, Director of the Engineering Experiment Station, and

*For description of other types of fatigue testing machines see:
Gough, "The Fatigue of Metals" (Van Nostrand, New York).
Moore and Kommers, "The Fatigue of Metals" (McGraw-Hill Book Company, New York).
Batson and Hyde, "Mechanical Testing," Vol. 1 (E. P. Dutton and Company, New York).
Templin, "The Fatigue Properties of Light Metals and Alloys," Proc. Am. Soc. for Testing Materials, Vol. 33, Part II, p. 364 (1934).
Schulz and Buchholz, "The Development of Fatigue Testing in Germany" (Über die Entwicklung der Dauerprüfung in Deutschland) Trans. New International Society for Testing Materials, 1931 Congress (Zurich).

TABLE 1

CAPACITY, SPEED, RANGE OF STRESS, AND POWER REQUIRED FOR FATIGUE TESTING MACHINES DESCRIBED IN THIS CIRCULAR

Machine	Shown in Figure	Speed r.p.m.	Horse-power of Motor	Maximum Load or Moment	Range of Stress During One Cycle
"Sondericker" type rotating-beam	1	1500	⅛	250 in.-lb. bending moment	Complete reversal
Cantilever type rotating-beam for 1-inch specimen	6	1000	½	10 000 in.-lb. bending moment	Complete reversal
Cantilever type rotating-beam for 2-inch specimen	8	1000	2	45 000 in.-lb. bending moment	Complete reversal
High-speed cantilever type rotating-beam	9	30 000	..*	12 in.-lb. bending moment	Complete reversal
Rotating-spring cantilever type	12	2500	½	300 in.-lb. bending moment	Complete reversal
Flat-specimen cantilever type	15	1200	⅛	150 in.-lb. bending moment	From constant (static) bending moment, through bending in one direction only, to complete reversal of bending moment.
Bending test attachment to repeated-torsion machine	23	1600	½	150 in.-lb. bending moment	Same as flat-specimen type
Repeated axial stress (tension-compression) machine	18	1000	1	2500 lb. tension or compression	From constant (static) tension, through cycles of tensile stress only, through complete reversal tension to compression, through cycles of compressive stress only, to constant (static) compression.
Repeated-torsion machine	21	1500	½	300 in.-lb. twisting moment	From constant (static) twisting moment, through twisting in one direction only, to complete reversal of twisting moment.

*Small air grinder motor used, with air pressure of 30 to 120 lb. per sq. in.

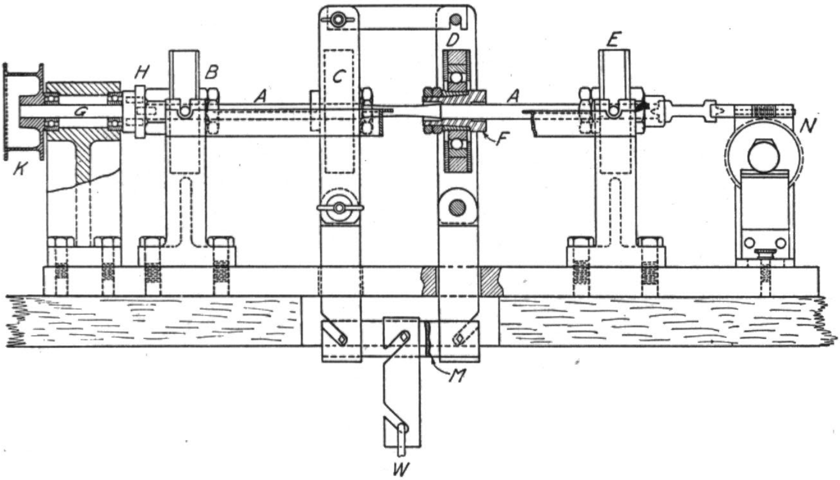

FIG. 1. SONDERICKER (OR FARMER) TYPE OF ROTATING-BEAM REVERSED-FLEXURE TESTING MACHINE
(Courtesy J. B. Hayes, Inc.)

of PROF. M. L. ENGER, Head of the Department of Theoretical and Applied Mechanics.

II. TESTING MACHINES FOR FATIGUE TESTS IN REPEATED FLEXURE

3. *Rotating-Beam Fatigue Testing Machines—Sondericker Type.*— The commonest type of fatigue testing machine is that used by Wöhler some 75 years ago for tests of specimens subjected to cycles of completely reversed flexure. This machine applies load to a rotating specimen in the form of a beam of circular cross-section which is loaded transversely with a known weight, and which is rotated by a motor. In this machine the rotating specimen may be either a cantilever beam or a simple beam loaded with one or more loads. The type used in the Materials Testing Laboratory of the University of Illinois is shown in Fig. 1 and Fig. 2. In this machine the specimen is a beam supported at the ends and loaded with two symmetrical loads. This form of machine was used by Sondericker in 1892.* It was later used by Farmer.* It has the advantage that the bending moment between the two points of loading is uniform, and that there is no shear between the points of loading. In Fig. 1 the specimen A is driven

*Sondericker, "Description of Some Repeated Stress Experiments," Technology Quarterly (Boston), April, 1932.
Farmer, "A Fatigue Testing Machine," Proc. Am. Soc. for Testing Materials, Vol. 19, Part II, p. 709 (1919).

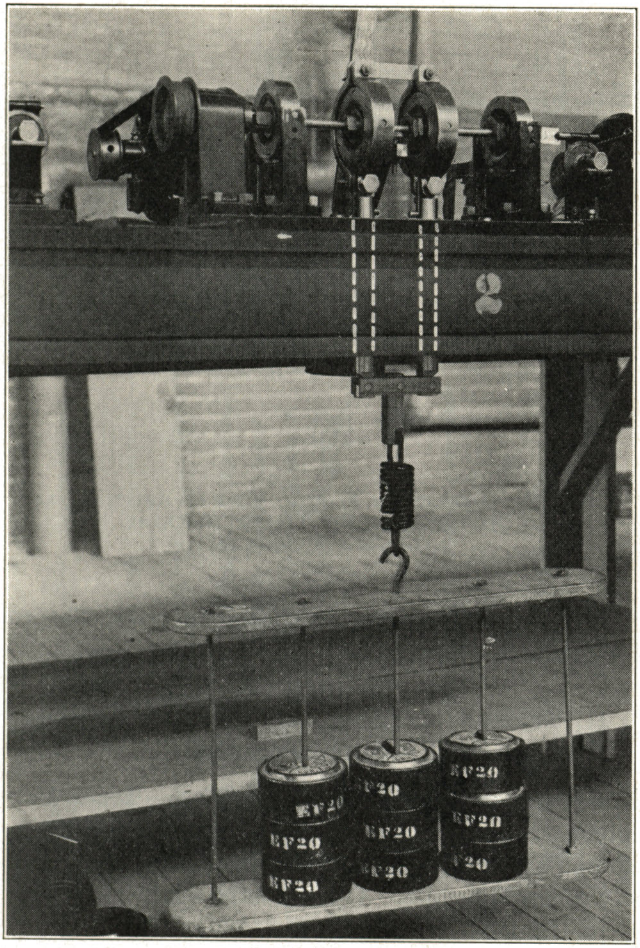

FIG. 2. ROTATING-BEAM FATIGUE TESTING MACHINE SHOWING WEIGHTS AND SPRING SUSPENSION

through a leather flexible coupling *H* by the drive pulley *K*. The specimen is mounted in ball bearings *B*, *C*, *D*, and *E*. A tapered collet fastens the specimen in each bearing, as is shown for bearing *D*. Gimbals attached to the two central bearings *C* and *D* carry an equalizer bar *M*, and from the middle of this bar are suspended weights *W*, hanging from a short helical spring. A counter *N* is driven by the specimen and when it breaks the counter automatically stops. When the specimen breaks the ball bearings *C* and *D* drop, and the ends of the specimen hit a trigger which releases a pivoted bar. This

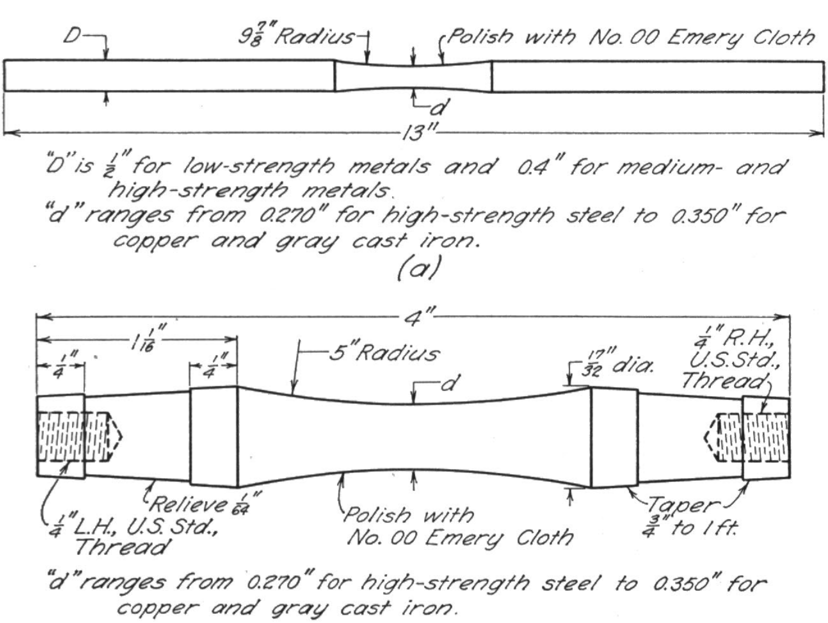

FIG. 3. SPECIMENS FOR SONDERICKER (OR FARMER) TYPE ROTATING-BEAM TESTING MACHINE

bar falls, and, in its fall, opens the switch controlling the motor. The speed of the rotating-beam machines of this type in the Illinois laboratory is 1500 r.p.m. Some laboratories use speeds as high as 3400 r.p.m.

4. *Specimens for Rotating-Beam Fatigue Testing Machine.*—Figure 3 shows the specimens used with this type of rotating-beam machine. In order to avoid failure of the specimens at the collets in bearings C and D owing to local stresses at the edge of the collets, the specimen is reduced over its center portion. This reduction is made by a lathe tool or a grinding wheel swung on a radius as the specimen is machined. It has been found very difficult to make a specimen in which the diameter is uniformly reduced over a central portion connected to the ends of the specimen with fillets, without having a slight ridge or raised portion at the junction of straight portion and fillet. The length of radius on which the cutting tool is swung has been arbitrarily fixed at $9\frac{7}{8}$ inches for the "long" specimen shown in Fig. 3 (a), and at 5 inches for the "short" specimen shown in Fig. 3 (b). In Fig. 11 is shown a small specimen with a smaller radius. Determina-

TABLE 2

ENDURANCE LIMITS FOR VARIOUS METALS AS DETERMINED BY DIFFERENT FATIGUE TESTING MACHINES

Metal	Testing Machine				
	Rotating Beam Fig. 1	Flat-Specimen Fig. 23	Krouse High-speed Fig. 9		Moore-Krouse Axial Load Fig. 18
	Speed—r.p.m.				
	1500	1200	10 000	30 000	1000
	Endurance Limit—lb. per sq. in.				
Structural Steel	30 000	33 000	32 000	33 000	32 000
Rail Steel	50 000	50 000	51 000	53 000	51 000
S.A.E. 4140 Heat-treated	91 000	......	91 000	93 000	91 000
Cast Iron	10 000	10 000	10 000	11 000	7 000*
Duralumin	15 000	15 000	15 000	16 000	15 000

*The low value for cast iron under reversed axial load may be due to the extreme sensitivity of that metal to any eccentricity of loading. Static tests of cast iron in direct tension frequently give unsatisfactory results, and the correlation between static tensile strength of cast iron and ultimate stress developed in a static flexure test has not been clearly determined.

tions of endurance limit for a variety of metals are given in Table 2, and it is to be noted that the radius of curvature used for the turned-down portion of the specimen apparently has no appreciable effect on the endurance limit for the different types of specimen used in the tests on which Table 2 is based.

The computed stress distribution along the specimens as given in Fig. 3 (a) and (b) is shown in Fig. 4, and it can be seen that, for a distance of about 0.05 inches each way from the middle of the length of the specimen the stress does not vary more than 1 per cent from the maximum. Figure 4 also shows the stress distribution along the other specimens described in this circular.

5. *Short Specimen and Attachments for Rotating-Beam Fatigue Testing Machine.*—The specimen shown in Fig. 3 (a) is so long that it is sometimes impossible to cut such a specimen from the metal available for testing, as for example in making fatigue tests of specimens from flat bars with the axis across the direction of loading. In such a case the specimen shown in Fig. 3 (b) may be used. To use this specimen in the rotating-beam machine requires special attachments

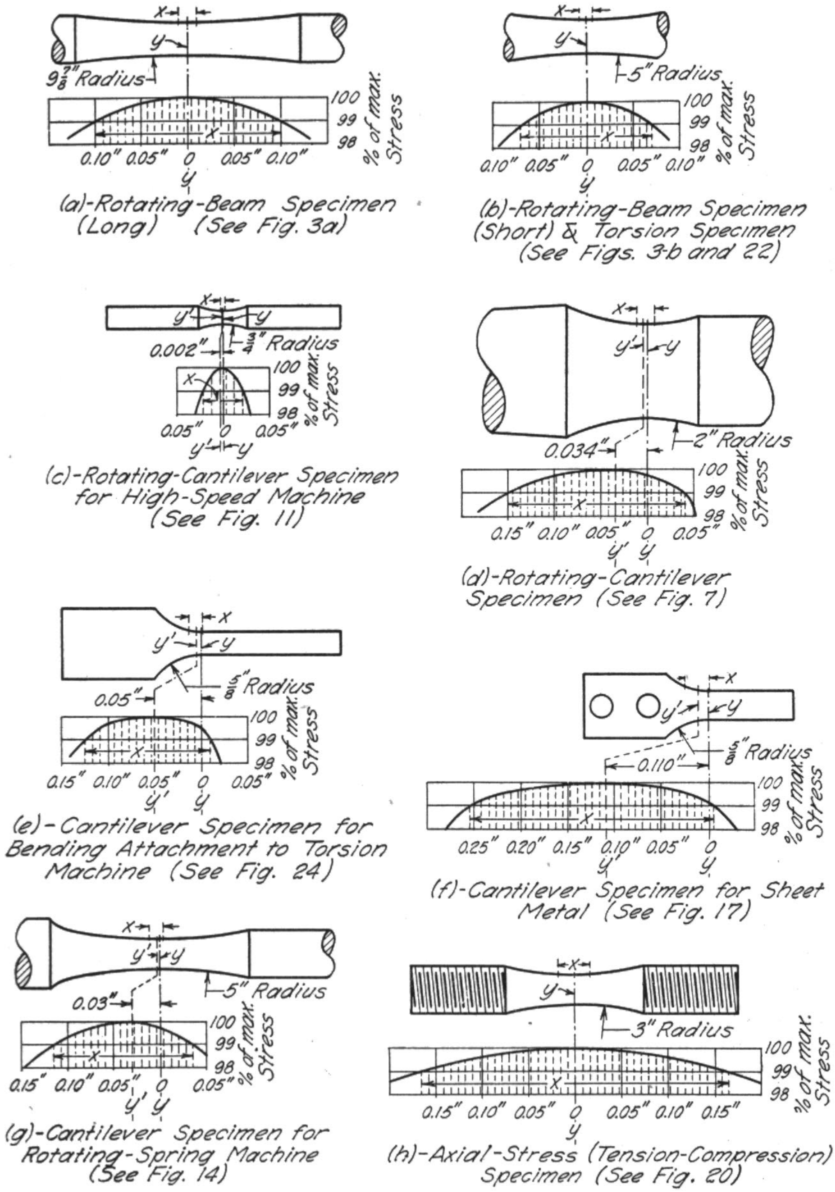

FIG. 4. STRESS DISTRIBUTION ALONG FATIGUE TESTING SPECIMENS

y y locates the cross-section of minimum size.
y' y' locates the cross-section of maximum stress.

In cases for which the cross-section of minimum size and that of maximum stress coincide (rotating-beam, specimen with symmetrical loads, torsion specimen, axial-stress specimen) only y y is shown. In the cantilever specimens the section of minimum size does not coincide with the cross-section of maximum stress, since for a short distance to one side of the cross-section of minimum size the bending moment increases at a greater rate than does the modulus of the cross-section.

x shows the length along the specimen for which there is not more than one per cent deviation from the maximum stress.

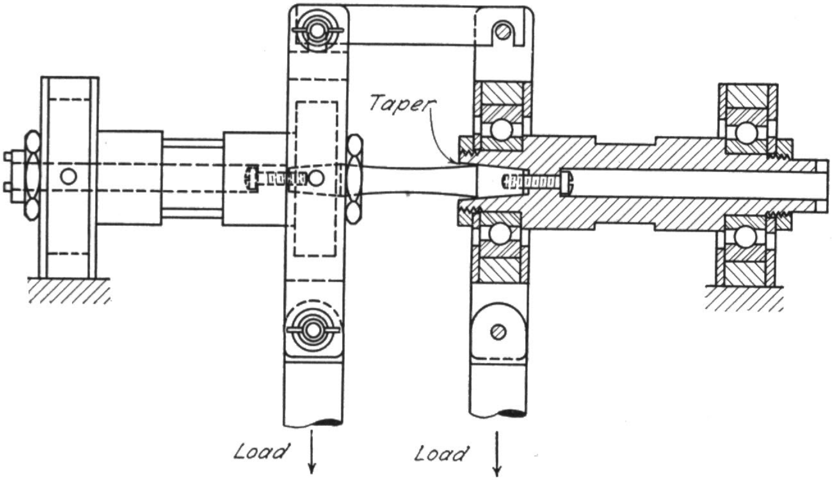

FIG. 5. ATTACHMENT TO ROTATING-BEAM TESTING MACHINE FOR TESTING SHORT SPECIMENS

shown in Fig. 5. This method of making holders for a short specimen has been used previously by Kommers* for a cantilever specimen, by Ono,† and by R. R. Moore,‡ whose fatigue testing machine is widely used in the United States.

6. *Cantilever Rotating-Beam Fatigue Testing Machine for 1-inch Specimens.*—The cantilever form of testing machine has some advantages over the rotating-beam form. It is somewhat simpler, and requires only three bearings instead of four. However, in a cantilever-type machine there is always present shearing stress as well as bending stress at the critical section. A cantilever-type machine for 1-inch specimens is shown in Fig. 6. The specimen is shown projecting from the middle bearing of the machine, and is loaded at its free end through a ball bearing by means of a calibrated helical spring. The shape of the specimen is shown in Fig. 7. It is held in a tapered chuck in the middle bearing of the machine. The revolution counter at the left-hand end of the machine is shown, and when the specimen breaks the bearing at the free end drops, striking a trigger and releasing suspended weights which pull open the switch of the motor.

Figure 8 shows a machine similar to that shown in Fig. 6, but designed to take specimens up to 2 inches in diameter at the critical

*Univ. of Ill. Eng. Exp. Sta. Bul. 124, p. 24. 1921.
†Memoirs Coll. Eng. Kyushu Imperial University, Vol. 2, No. 2. 1921.
‡Proc. Am. Soc. for Test. Mat., Vol. 26, Part II, p. 259. 1926.

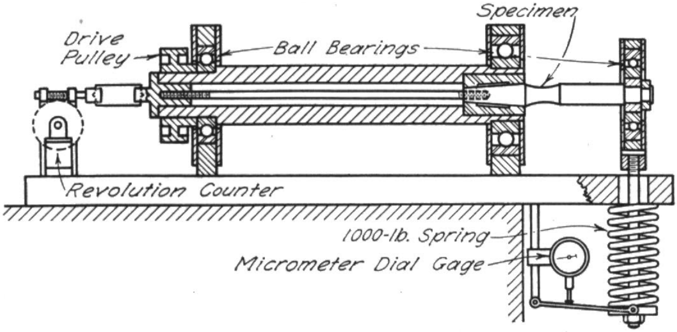

FIG. 6. ROTATING-CANTILEVER FATIGUE TESTING MACHINE FOR SPECIMENS ONE INCH IN DIAMETER

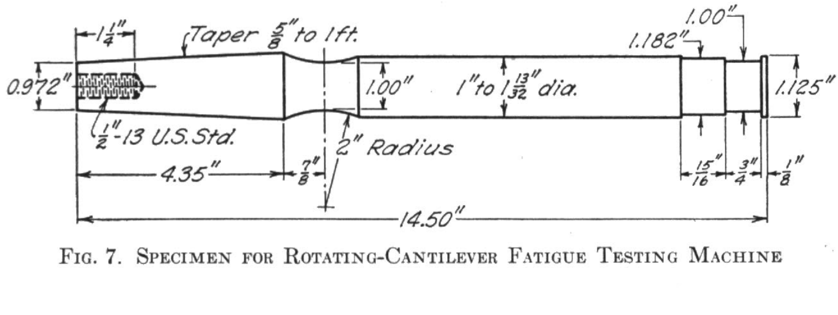

FIG. 7. SPECIMEN FOR ROTATING-CANTILEVER FATIGUE TESTING MACHINE

section. This machine has been especially useful in connection with tests in which the growth of a fatigue crack is studied by direct examination. A low-power microscope is shown mounted on the front main bearing of the machine. As a fatigue test proceeds the machine is stopped at intervals, and an examination made round the circumference at the critical section of the specimen to detect and measure any fatigue cracks which form.

7. *High-speed Cantilever Rotating-Beam Fatigue Testing Machine.*—A major obstacle to the general adoption of repeated-stress tests to determine the fatigue strength of metals is the long time required to carry out such tests. Using a speed of 1500 r.p.m. it takes about a week to determine an endurance limit for a ferrous metal, and much longer for some non-ferrous metals. Various accelerated tests have been proposed, but none as yet devised has proven thoroughly reliable. Increasing the speed of application of cycles seems a more promising way of shortening the time required to get fatigue test results, since over a wide range of speeds it has been found that the

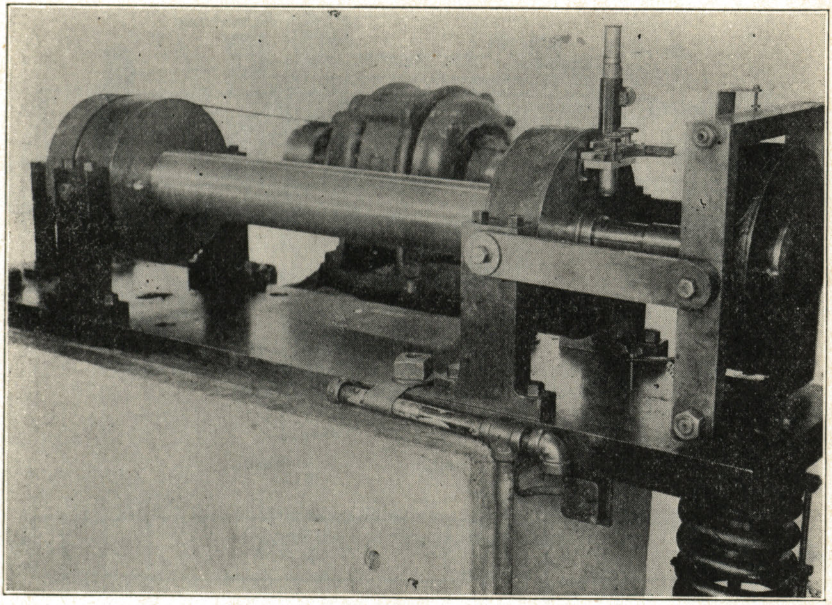

FIG. 8. ROTATING-CANTILEVER FATIGUE TESTING MACHINE FOR SPECIMENS TWO INCHES IN DIAMETER

speed of the machine has very little effect on the endurance limit of most metals used in construction.*

The rotating-beam type of testing machine seems well fitted for high-speed operation. High speed of rotation may be obtained in several ways: (1) By the use of a high-speed series-wound electric motor speeds as high as 10 000 r.p.m. may be obtained, but sparking is likely to cause brush and commutator troubles; (2) a special high-speed induction motor may be used, but a special source of high-frequency alternating current is required; (3) high speed may be secured by means of a worm gear driving a high-pitch worm, but problems of lubrication and wear of the thrust bearing have to be solved; (4) direct drive by multiplying spur gears may be used, but noise and wear of gear teeth present difficulties; (5) speed multiplication by belting may be used, but problems of bearing friction arising from the necessary tightness of belt are present; (6) an air turbine or a steam turbine may be used as a drive, and speeds of 30 000 r.p.m., or even higher, may be secured, if a reliable system of lubrication is installed.

*Univ. of Ill. Eng. Exp. Sta. Bul. 124, p. 27, and Bul. 136, p. 58.

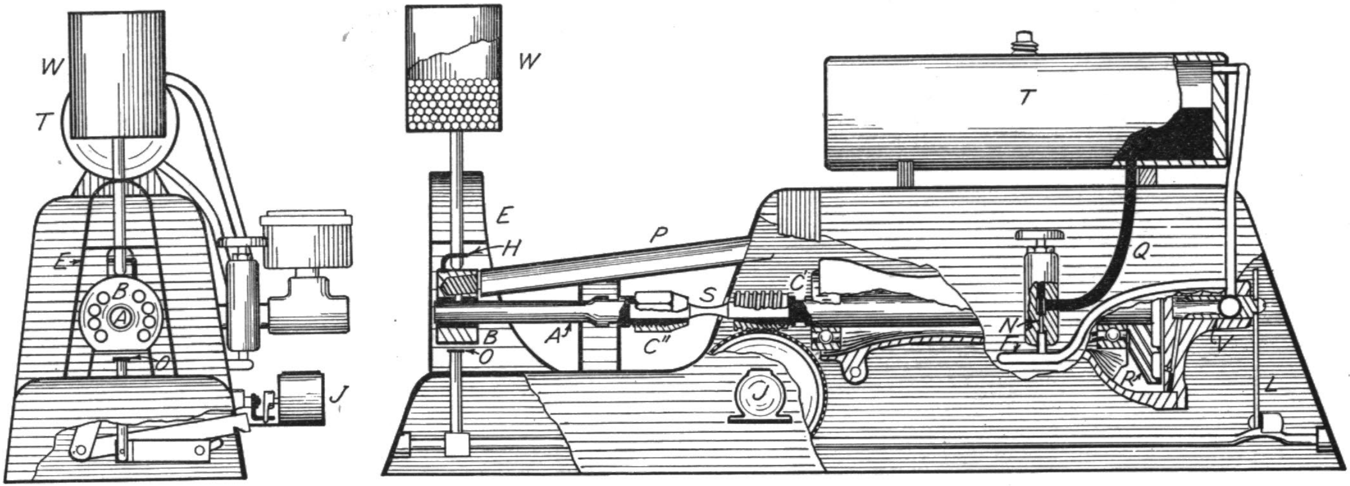

FIG. 9. KROUSE HIGH-SPEED ROTATING-CANTILEVER FATIGUE TESTING MACHINE

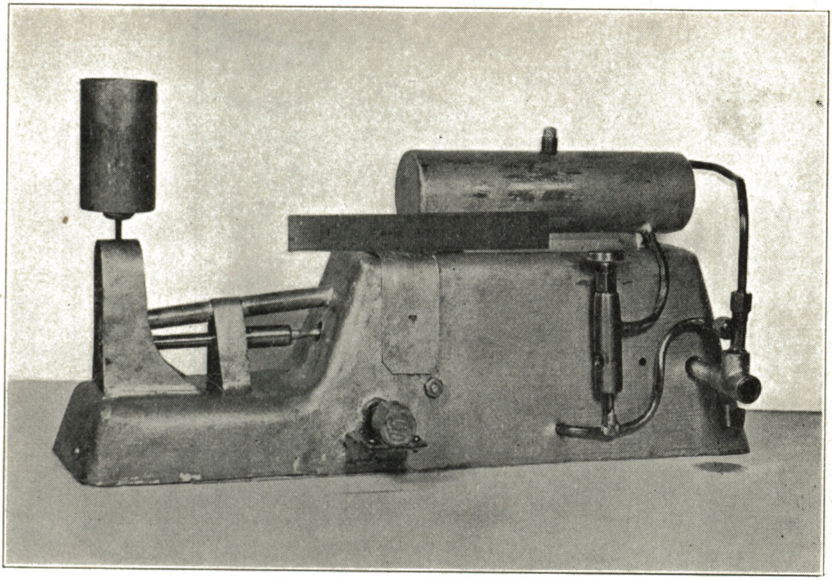

FIG. 10. KROUSE HIGH-SPEED ROTATING-CANTILEVER FATIGUE TESTING MACHINE

Figure 9 shows a sectioned drawing, and Fig. 10 is from a photograph of a rotating-cantilever testing machine driven by a commercial air turbine, operating under air pressure of from 30 to 120 lb. per sq. in. This machine has been in successful use for over a year in the Materials Testing Laboratory of the University of Illinois. It was designed and constructed by Mr. G. N. Krouse. The specimen S is held at one end in the three-pronged driving chuck C' on one end of the turbine shaft. The other end of the specimen is held in a similar chuck C'', which is attached to one end of the lever arm A, whose other end rotates in an air-cooled plain bearing B. The loading weight W, consisting of a variable weight of lead shot, is supported on the bearing B through a slender rod which is guided through holes in the support E. The bearing B is prevented from moving from its working position by a steel wire hook H.

The ball bearing rotor shaft of the turbine is driven by a disc rotor R, which, in turn, is driven by a high-velocity blast of air impinging on the rotor blades. Air under pressure is fed to nozzles through a quarter-turn valve V. When a specimen fractures the bearing B and the loading weight drop on the cut-off button O, this releases the spring-actuated lever arm L, closes the air valve V, and stops the turbine.

A revolution counter J records the number of cycles of stress, and is driven by a 100-to-1 worm gear reduction. The nut on the driving chuck C' serves the dual purpose of tightening the chuck on the specimen S and acting as the worm to drive the gear which turns the shaft of the revolution counter.

Continuous, constant speed operation of the turbine, and satisfactory wearing conditions in the bearings depend largely upon satisfactory lubrication; such lubrication is provided by a continuous spray of oil. In Fig. 9 the air-tight tank T is maintained under air-line pressure through the tube Q. Tube F leads from tube Q, and ends in a small orifice through which oil is sprayed into the ball race next to the rotor R. A steady stream of air flows through tube F, and the small orifice to impinge on the ball bearings, while a small amount of oil flows through the needle valve N into the tube F, where it is caught in the air stream, and a fine spray of air and oil issues to lubricate the bearing. Since the differential pressure across the needle valve N is due to the static head of oil above it, changes in the air line pressure do not affect the oil flow.

The oil spray, after emerging from the bearing near the rotor R, is caught up by the exhaust air and carried along the turbine shaft towards the exits surrounding the ball bearing next to the chuck C'. Part of the oil spray passes through this bearing, and a part of the spray, after leaving the turbine, is carried through the oil pipe P and lubricates the load bearing B. The remainder of the exhaust air-oil spray is deflected downwards to the base of the machine, where the oil in the spray is caught in a pan (not shown in Fig. 9) while the air escapes round the edges of a galvanized iron box, which covers up the entire machine while in operation. The oil collected in the pan is filtered, and used to refill the tank T. One filling of oil, about one-third of a pint, will keep the machine lubricated for about two days. Very little oil is carried away with the air which escapes round the edges of the box which covers the machine while in operation.

In Table 2 are given determinations of endurance limit for a number of common metals as obtained on various types of machines used in the laboratory, and for various speeds of operation. It can be seen that up to 30 000 cycles of stress per minute no very marked variation of endurance limit is shown by different rotating-beam machines. Hence even a considerable variation of speed of the air-turbine machine would have little effect on the test results. The speed of the machine is controlled with a fair degree of constancy by means of a gate valve on the air line. A pressure gage shows the pressure available. The speed of the turbine may be varied from 5000 to 30 000 r.p.m.

The specimen S is fastened in the chucks C' and C'' by means of a pair of end wrenches. The chuck C' is accessible through an opening in the machine case just above the chuck C'. This opening is kept closed during operation of the machine by means of a metal strip. It may be noted that no difficulty has been experienced in making the lever arm A run true.

The loading weight on the specimen consists of the weight of the bearing B, of the supporting rod, of the shot container W, of the shot in it, and of a proportionate part of the lever arm A. The "arm" of this weight is the distance from the axis of the supporting rod to the critical section of the specimen. This distance is measured by means of a trammel type divider. One point of the divider is placed in the holes of the weight support E, and the other is adjusted to reach the critical section of the specimen. The distance is then measured along a steel scale. The bending moment, then, is equal to weight times arm, and the extreme fiber stress is computed by the ordinary flexure formula.

The outstanding advantage of this machine is the high speed possible. Another advantage is the simple form of specimen, and the low cost of machining it. The small size of specimen makes it possible to make fatigue tests of metal when only very short pieces can be obtained. The machine is not expensive to make, and is light, portable, and self-contained. The disadvantages of this machine are the small bending moment possible, the care necessary to see that its lubrication system is kept in proper operation, the necessity of supplying a source of compressed air, and, in common with all rotating-beam machines, the limitation of its range of stress to cycles involving complete reversal of stress.

8. *Specimen for High-speed Cantilever Rotating-Beam Fatigue Testing Machine.*—The specimen for the Krouse high-speed rotating-beam fatigue machine is shown in Fig. 11. The diameter d varies from 0.200 inch for specimens of gray cast iron to 0.090 inch for specimens of heat-treated alloy steel. The specimen requires only a small amount of metal, and, as compared with the specimens shown in Fig. 3 (a) and 3 (b), it is inexpensive to machine.

9. *Advantages and Limitations of Rotating-Beam Fatigue Testing Machines.*—The great advantage of the rotating-beam testing machine is its simplicity, its low cost, the high speed at which it can be run, and the accuracy with which load and bending moment can be

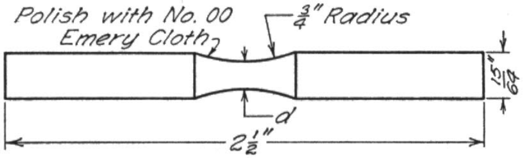

FIG. 11. SPECIMEN FOR KROUSE HIGH-SPEED ROTATING-CANTILEVER FATIGUE TESTING MACHINE

measured. Probably no other type of fatigue machine gives so accurate a measure of the range of stress applied. The drawbacks of the machine are three-fold: (1) The only range of stress which can be conveniently tested is that of complete reversal; this type, therefore, cannot be used at all conveniently for studying the effect of range of stress. (2) It is very difficult to use any other form of specimen than one with a circular cross-section; the machine is not adapted for testing thin sheet metal or irregular shapes.* (3) The machined specimen as shown in Fig. 3 (a) is quite expensive, and the short specimen, shown in Fig. 3 (b), with its more elaborate machining is even more expensive. For the rather small lots of specimens machined at one time in the Materials Testing Laboratory machine shop it has rarely been possible to produce a rotating-beam specimen of either of the types shown in Fig. 3 at a cost of less than two dollars, while for the production of specimens like those shown in Fig. 3 (b) cut out of railroad rails the cost is about six dollars per specimen. The cost of the small specimens for the Krouse high-speed machine is decidedly lower.

10. *Rotating-Spring Fatigue Testing Machine.*—Occasionally it is desirable to have a testing machine in which the specimen is stationary. This is especially true in cases where it is desired to measure accurately the temperature of the specimen during test. The machine shown in Figs. 12 and 13 was designed in the Materials Testing Laboratory of the University of Illinois, and built by J. B. Hayes, Inc., Urbana, Illinois. One end of the specimen *S* is held rigid in the vise *V*, and the other end, which runs in the bearing *B*, is rotated in a small circle. Sidewise pressure, which can be adjusted by means of a hollow screw *U*, Fig. 13, is brought on the bearing *B* through a calibrated indicator spring *I*. Sidewise motion of the bearing *B* is prevented by swinging the bearing on a pivoted arm, and excessive displacement of the bearing after the specimen breaks is prevented by the rod *D*,

*Bulletin 183, Engineering Experiment Station, University of Illinois, Urbana, Illinois, pages 7 to 15, gives the description of the adaptation of this type of machine to fatigue tests of turbine blade shapes. On account, however, of the varying deflection of the specimen as it was rotated, it was necessary to run the machine at a speed not greater than 130 r.p.m.

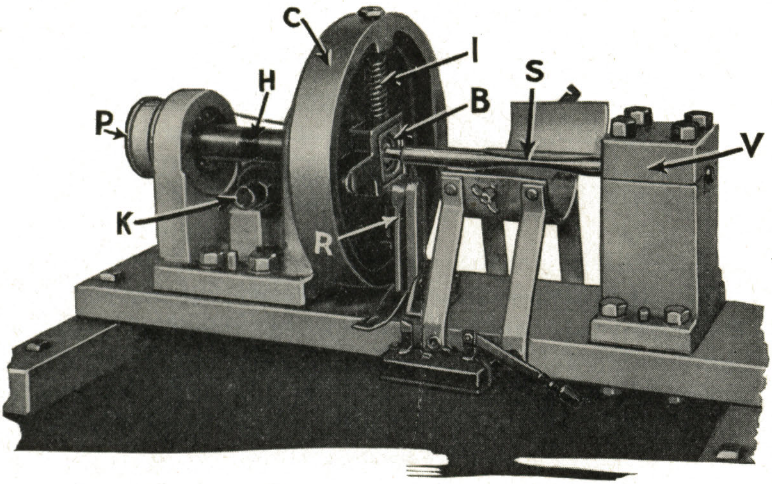

FIG. 12. ROTATING-SPRING REVERSED-FLEXURE FATIGUE TESTING MACHINE
(Courtesy J. B. Hayes, Inc.)

Fig. 13. The rotating head C is driven by a shaft H, a pulley P, and a motor not shown. The speed of rotation commonly used is 2500 r.p.m. The number of revolutions of the shaft is measured by the counter K which is driven by a worm on the drive shaft. As shown in Fig. 12 the breaking of the specimen throws out the catch R, releasing a spring which opens the knife switch controlling the motor. A later shut-off arrangement consists of an arm above the specimen, which, when a specimen breaks, strikes a releasing trigger, allowing a mercury switch to drop and to open the motor circuit.

Figure 13 shows the method of measuring the compression of the spring I, and hence measuring the load and the bending moment on the specimen. To the plunger of a micrometer dial M is attached a nose N which just fits inside the hollow screw U. The spring I is compressed by screwing up U. This, of course, is done while the machine is stationary. Then the nose of the micrometer dial M is thrust through the hole in U and shoved down until the collar X rests on a machined flat spot on the circumference of the rotating head C. The reading of the dial then measures the compression of the specimen. Usually several springs are supplied with each machine, and each spring is calibrated by means of dead weights, using the micrometer dial and a special fixture to hold the spring.

The determination of the compression of the spring, and hence the bending moment on the specimen, is, of course, made when the ma-

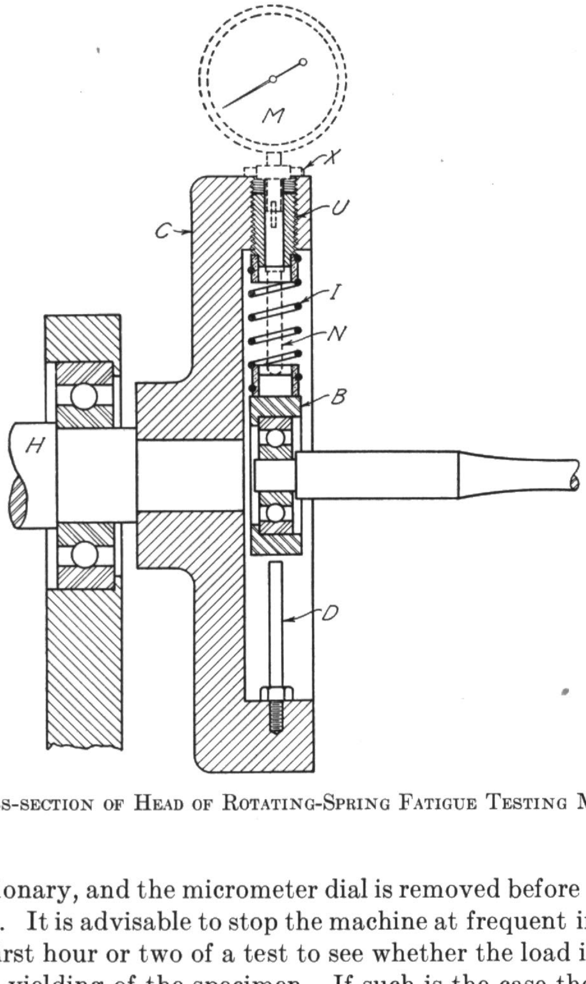

FIG. 13. CROSS-SECTION OF HEAD OF ROTATING-SPRING FATIGUE TESTING MACHINE

chine is stationary, and the micrometer dial is removed before starting the machine. It is advisable to stop the machine at frequent intervals during the first hour or two of a test to see whether the load is falling off owing to yielding of the specimen. If such is the case the load is increased to its desired value. Usually the load stays very nearly constant after the first few hours of test.

Figure 14 shows the specimen used in the Illinois laboratory with the rotating-spring testing machine. A description of the fittings used with this machine for fatigue tests of metals at high temperatures is found in the Proceedings, American Society for Testing Materials, Vol. 31, Part I, page 114 (1931).

11. *Advantages and Limitations of Rotating-Spring Fatigue Testing Machine.*—The principal advantage of the rotating-spring machine is the fact that the specimen is stationary. This is of advantage if

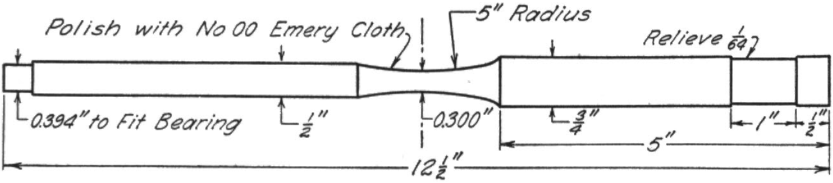

FIG. 14. SPECIMEN FOR ROTATING-SPRING FATIGUE TESTING MACHINE

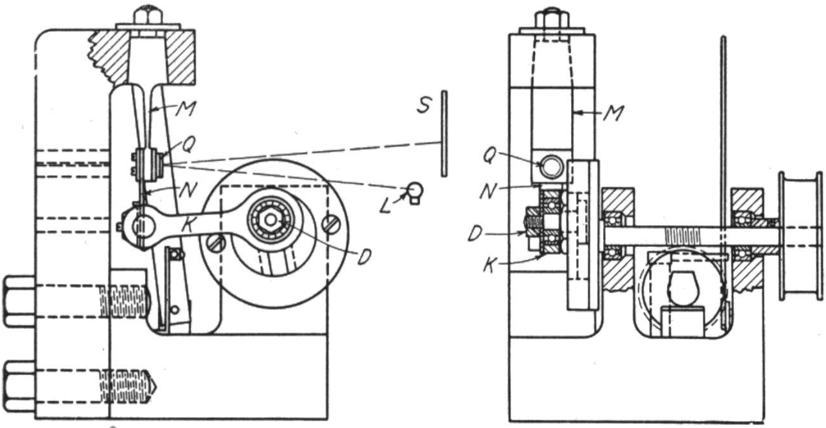

FIG. 15. THIN-SPECIMEN REPEATED-FLEXURE TESTING MACHINE SHOWING DIAGRAM OF OPTICAL SPRING-DEFLECTION INDICATOR

examination of the specimen is desirable while the test is proceeding and, as noted previously, in cases where it is desired to measure accurately the temperature of the specimen during a test.

The disadvantages lie in the fact that the measurement of load by the compression of a spring is less accurate than the measurement of load by dead weights, that, especially during the earlier part of the test, it is necessary to stop the machine occasionally and readjust the load, and that at the fracture of the specimen it is not quite so certain that the knock-off arm will release the motor switch,—this is especially true in the case of the testing of soft materials or metals at high temperatures. Like the rotating-beam machine the rotating-spring machine cannot be very easily adapted for tests over a varying range of stress.

The first cost of the machine, the speed of the machine, and the cost of machining a specimen are not widely different from the corresponding costs for fatigue tests in the "Sondericker" type of testing machine.

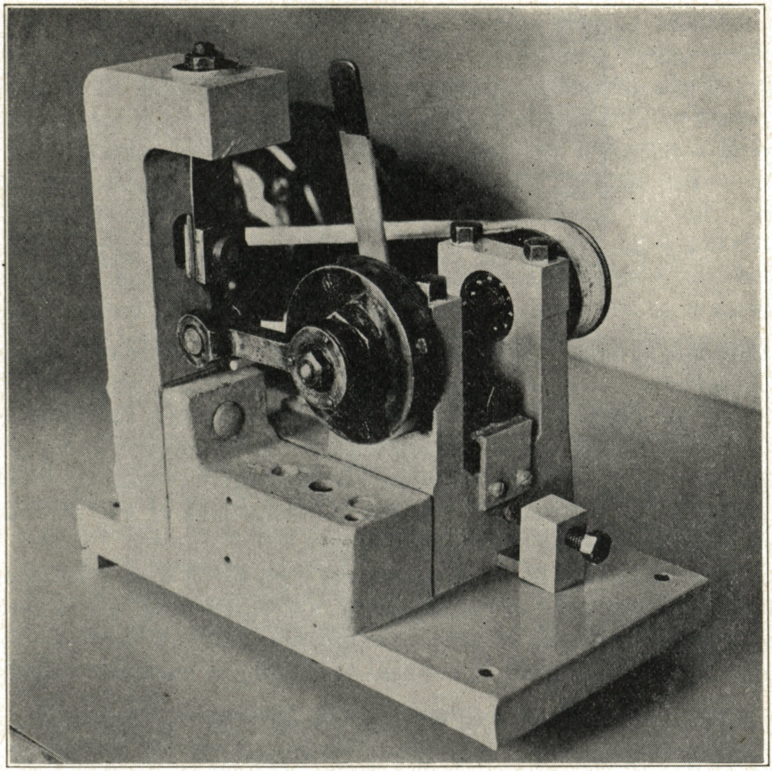

FIG. 16. THIN-SPECIMEN REPEATED-FLEXURE TESTING MACHINE SHOWING ADJUSTMENT FOR VARYING RANGE OF STRESS

12. *Fatigue Testing Machine for Flat Specimens.*—Figure 15 shows a repeated-stress testing machine for making flexural fatigue tests of specimens from thin sheet metal and of specimens from near the surface of thick metal. Figure 16 is from a photograph of this machine. The machine applies repeated stress by flexure set up by means of a variable-throw crank and connecting rod, and gives a measure of the stress set up by the deflection of a short flat steel spring.

The specimen N is fastened at one end to the calibrated flat spring M, and the other end of the specimen is vibrated back and forth by the connecting rod K, which is operated by the variable-throw crank D. If the throw of the crank is increased the bending moment and the stress on the specimen are increased, and the deflection of Q (a mirror attached to the calibrated spring) is also increased, causing motion of a beam of light reflected from the lamp L to the screen S. The motion

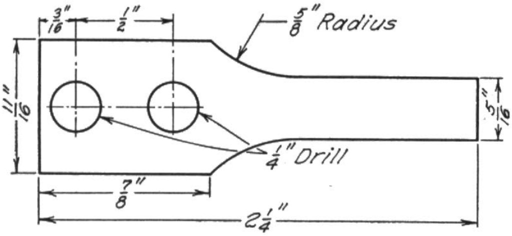

FIG. 17. SPECIMEN FOR FATIGUE TESTS OF THIN SHEET METAL

of the beam of light along the screen S is, then, a measure of the stress in the specimen. There is provided an automatic trip which is operated by the dropping of the connecting rod K when the specimen breaks. The falling connecting rod releases a pivoted arm, which falls, opens the motor switch, and stops the machine. A counter is also provided which records the number of revolutions of the machine. This machine is usually run at 1200 r.p.m.

As shown in Fig. 16 the machine has been fitted with a screw adjustment by which the specimen, spring, and supporting "goose neck" can be moved back and forth, changing the range of bending from complete reversal of bending moment to bending in one direction only.

13. *Calibration of Fatigue Testing Machine for Flat Specimens.*—Before running any tests, it is necessary to calibrate the springs M of the fatigue machine. After removing the connecting rod K and the pin D, a steel calibration specimen is placed in the machine. Known bending moments are applied to the steel specimen, at the point of contact of the connecting rod, by means of a horizontal steel wire passing over a pulley and loaded with dead weights. The relation between these bending moments and the corresponding deflections of the ray of light on scale S gives a calibration diagram for the spring M. For convenience in laboratory procedure a curve is drawn having the deflections of the beam of light plotted against the calculated bending moments on the critical section of the specimen. The bending moments for any scale reading in a test are then read from the spring calibration data.

14. *Flat Specimens for Fatigue Testing.*—Figure 17 shows the specimen used with the testing machine shown in Figs. 15 and 16. With this specimen the surface may be either polished or left as received.

15. *Advantages and Limitations of Fatigue Testing Machine for Flat Specimens.*—The advantage of the flat specimen testing machine lies in its ability to make fatigue tests on thin sheet metal and to make fatigue tests from different parts of a piece of metal. For example, thin flat specimens can be cut which will show the difference in fatigue strength between the cold-rolled metal at the running surface of a railroad rail and the metal at the center of the head of the rail. With a thin-specimen machine with optical lever to record deflection of the calibrated spring, it is possible by rotating a radially slotted disc in the space between the mirror Q and the scale S to show the wave form of the cycle of stress, and to detect any abnormal stresses which may be present.

The disadvantages are the somewhat lowered accuracy due to the use of a calibrated spring for measuring load, and the necessity of occasionally stopping the machine to readjust the load. The cost of the machine, its speed, and the cost of machining specimens are not greatly different from the corresponding costs of the "Sondericker" type of rotating-beam machine.

A special attachment for flexure tests, which may be attached to a torsion machine, is described in the chapter on torsion fatigue machines.

16. *General Advantages and Limitations of Repeated-Flexure Fatigue Testing Machines.*—The outstanding advantages of the repeated-flexure type of machine are its simplicity, its low cost, and the high speed at which it can be operated. The outstanding limitation is the inability to determine true stresses if any part of the specimen is stressed above the elastic range. Usually the endurance limit is within the elastic range for completely reversed stress, but this is not the case for annealed copper or very soft iron, or such metals as lead and zinc.

When it is important that stress above the elastic range be accurately determined, some form of direct tension-compression machine is to be preferred to a flexure machine.

III. Testing Machine for Fatigue Tests in Direct Tension and Compression

17. *Fatigue Testing Machine for Axial Loads (Direct Tension-Compression).*—For fatigue tests at stresses beyond the elastic range of a metal a machine producing direct axial stress on the specimen allows a much more accurate computation of stress than does a ma-

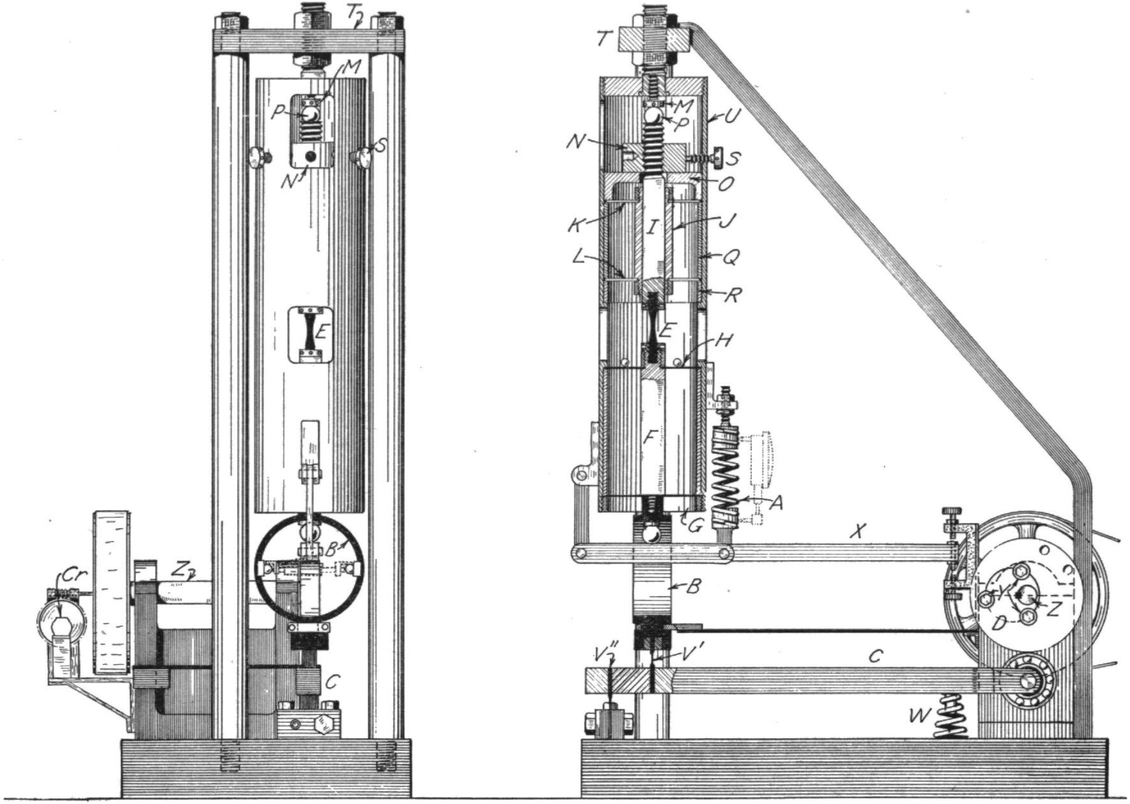

Fig. 18. Moore-Krouse Axial-Stress (Tension-Compression) Fatigue Testing Machine

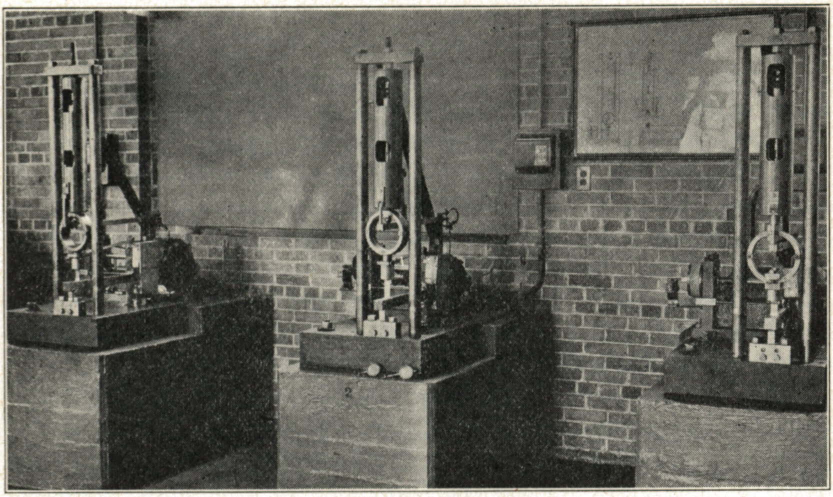

FIG. 19. BATTERY OF THREE AXIAL-STRESS (TENSION-COMPRESSION) FATIGUE TESTING MACHINES

chine producing stress by flexure, since direct axial stress is equal to load divided by area of cross-section above the elastic range as well as below, while the flexure formula for stress becomes quite inexact once the elastic range is passed.

Figure 18 shows a section drawing of a repeated axial-stress testing machine designed in the Materials Testing Laboratory of the University of Illinois and constructed partly in the laboratory shops, and partly by J. B. Hayes, Inc., Urbana, Illinois. Figure 19 is from a photograph of a battery of three of these machines. Load is applied from a drive shaft Z on which is a double eccentric D, which constitutes a variable throw cam, the throw being varied by rotating the outer eccentric over the inner, and locking in position by means of the cap screws Y. This cam acts on a ball bearing to vibrate the lever C against the spring W. This lever is fitted with plate fulcra V' and V''. Through V' varying tension is applied to the calibrated elastic ring B, thence through shaft F to the specimen E, and finally through the outer shell U and cross-head T to the frame of the machine. Through the calibrated helical spring A steady compression of any desired amount can be superimposed on the variable tension set up by the motion of the lever C, and any desired ratio of maximum to minimum stress secured. The horizontal deflection of the elastic ring B during a cycle of stress, and the (nearly) steady deflection of the helical spring A are measured by micrometer dial strain gages, shown in broken lines in Fig. 18. A revolution counter Cr records the number of cycles of stress. When a specimen breaks, the shaft F drops, slightly pushing down the end of the lever X, and operating a circuit breaker in the motor circuit. The machine is run at a speed of 1000 r.p.m.

The shaft F is guided by two elastic diaphragms G and H, and when making a test the specimen E is screwed into the lower shaft F and the upper shaft I, then the diaphragms are levelled by adjusting the nut N until the steel balls on diaphragm G show no tendency to run to one particular place on the circumference of the diaphragm. The total deformation of the specimen E and the system above it is not more than 0.005 inch during a test, hence the load carried by the diaphragms is negligible if they are properly adjusted.

In a repeated-stress machine for axial loading the centering of the specimen is of extreme importance. The centering adjustment for the specimen E consists of an upper shaft I guided by its sliding fit in the sleeve J. The diaphragms K and L are somewhat smaller in diameter than the bore of the outer shell U, and they maintain the lateral position of the sleeve J, and hence the upper shaft I and the specimen E, by being locked into position between the ends of the inner shells Q and R and the locking cap O by pressure from the stud M acting through a spherical seat P on the upper end of shaft I, and the reaction of nut N against the locking cap O. While locking the centering parts together their initial centered position is maintained by bringing three screws S, set 120 degrees apart, to bear against the lateral surface of the nut N.

A temperature change in length of supporting pillars under the cross-head T is very nearly compensated by an equal and opposite temperature change in length of the shell, ring, and elastic connections. Variations in stress caused by temperature changes during a test are negligible.

Especially during the first hours of a test there is likely to be some change in range of stress due to plastic deformation of the specimen E. This should be watched, and the reading of lateral deformation of the elastic ring B taken at rather frequent intervals until it settles down to a steady value. However, before this change can become very serious the stretch of the specimen will cause the lever X to move downward sufficiently to close the contact at its outer end, and to operate the circuit breaker in the motor circuit. The action of this lever and contact is sufficiently delicate to stop a test before complete fracture of the specimen has taken place.

Once the specimen has "settled down" to a steady range of load the machine requires little attention during a test, even one extending

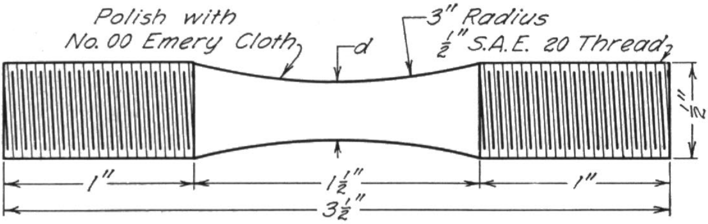

FIG. 20. SPECIMEN FOR AXIAL-STRESS (TENSION-COMPRESSION) FATIGUE TESTING MACHINE

over several days. The machine is mounted on a heavy concrete base, as is shown in Fig. 19.

18. *Tests of Correctness of Centering of Specimen in Axial-Load Machine.*—(a) Roll the specimen to be tested on a flat piece of plate glass to see that its axis is straight. Then subject it to several thousand cycles of load, and after removing it from the machine repeat the rolling test on plate glass.

Or (b) place a specimen in the machine as if for a test. Adjust the centering head and fix the diaphragms. Without applying load, loosen the two specimen locking nuts and try whether the specimen may be freely turned in the closely fitted threaded sockets in the shafts F and I.

A still more convincing test of the correct action of the axial-load machines, and incidentally of the different types of flexure machines in the laboratory, is furnished by comparative values of endurance limit determined for different materials by different machines. Table 2 shows the results of a series of such tests. The close correspondence of the endurance limits determined by various machines is evident, except in the case of cast iron, and it will be remembered that even in static tests of cast iron it is difficult to correlate the results of tension tests and flexure tests. The general results shown in Table 2 give ground for confidence in the accuracy of the different types of machine there compared.

19. *Specimen for Fatigue Testing Machine for Axial Loads.*—The specimen used with the axial-load fatigue machine is shown in Fig. 20. The diameter d varies from 0.400 inch for specimens of gray cast iron to 0.100 inch for specimens of rail steel and of heat-treated alloy steels.

20. *Advantages and Limitations of Fatigue Testing Machine for Axial Loads.*—The principal advantage of an axial-load fatigue test-

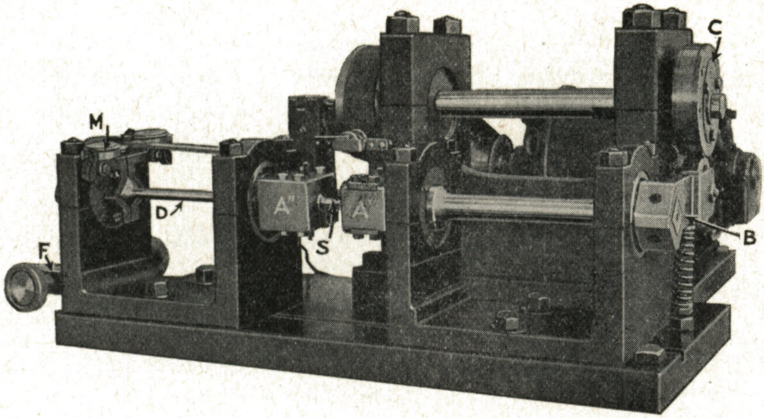

FIG. 21. REPEATED-TORSION FATIGUE TESTING MACHINE
(Courtesy J. B. Hayes, Inc.)

ing machine lies in the fact that, in an axially loaded specimen, stress can be accurately computed even beyond the elastic range of a metal. This feature is of especial advantage when making tests under cycles of stress varying from a minimum value to a maximum value in the same direction, e.g. from a minimum tension to a maximum tension. In this case the stress at endurance limit very frequently is beyond the primitive elastic range of the metal, and it cannot be very accurately computed for a flexure specimen.

The limitations of the axial-load type of machine are its high first cost, and the fact that the highest accuracy in the measurement of forces is not secured by measuring the deformation of any elastic measuring device, such as a ring or a spring.

IV. TESTING MACHINE FOR FATIGUE TESTS IN TORSION

21. *Repeated-Torsion Fatigue Testing Machine.*—For determining shearing strength under repeated stress some form of fatigue testing machine designed to set up cycles of torsion is convenient. Figure 21 shows a repeated torsion machine of which three are in service in the Materials Testing Laboratory of the University of Illinois. This machine, although designed independently at Illinois, is very similar to one designed by G. A. Hankins of the British National Physical Laboratory.* A description of the Hankins machine was received at Illinois while the Illinois machine was under construction.

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*Hankins, "Torsional Fatigue Tests on Spring Steels," Special Report No. 9, Engineering Research, Department of Scientific and Industrial Research, H. M. Stationery Office, London, Eng.

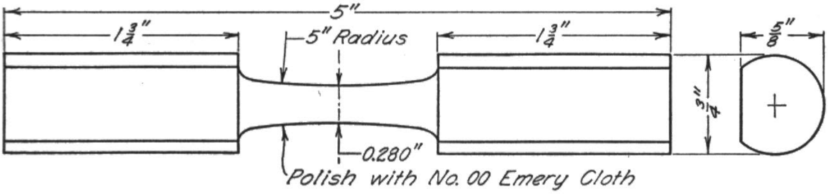

FIG. 22. SPECIMEN FOR REPEATED-TORSION FATIGUE TESTING MACHINE

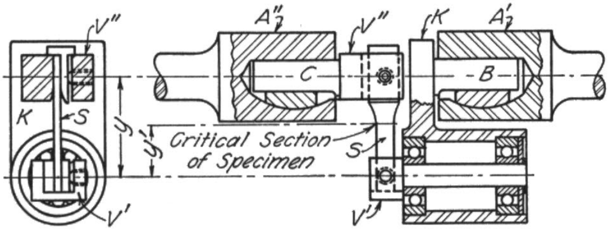

FIG. 23. ATTACHMENT TO REPEATED-TORSION FATIGUE TESTING MACHINE FOR MAKING REPEATED-BENDING TESTS

Torsion in the specimen S is set up through the chuck A' and the lever arm B by the variable-throw cam C. This cam consists of a double eccentric, and the throw of the eccentric is adjusted by turning the outer eccentric round the inner and clamping in any desired position. The machine operates at 1500 r.p.m. The torsion is transmitted through jaw A'' to a calibrated specimen D, the twist of which is proportional to the twisting moment on the specimen, and is measured by dial gages M.* When starting a test the desired range of twisting moment is put on the specimen by turning the machine over by hand, and adjusting the throw of the cam C and the initial twisting moment on bar D and specimen S, by means of the screws F, which act on a radial arm attached to the left-hand end of the bar D. The range of twisting moment can be varied from complete reversal to torsion in one direction only, and the maximum twisting moment in a cycle can be given any value up to the capacity of the machine, 300 inch pounds. The specimen S is held from turning in the chucks A' and A'' by means of broad keys bearing against flattened areas on each end of the specimen.

22. *Specimen for Repeated-Torsion Fatigue Testing Machine.*—Figure 22 shows a torsion specimen for use with the machine shown in

*The plungers of the dial gages M are held back out of contact with the arm on the calibrated specimen D when the machine is running.

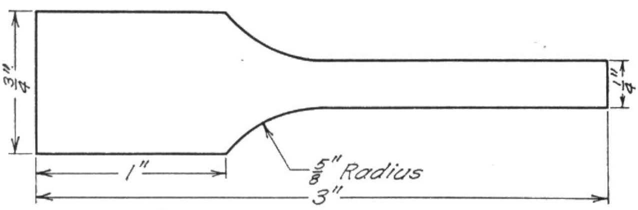

FIG. 24. SPECIMEN FOR REPEATED-BENDING ATTACHMENT TO REPEATED-TORSION FATIGUE TESTING MACHINE

Fig. 21. The circular ends of the specimen are flattened at the surface and are held in chucks A' and A'', Fig. 21, by means of broad keys. This is shown more clearly in Fig. 23, which shows a bending attachment, with the ends of the attachment B and C held as a torsion specimen is held.

23. *Calibration of Repeated-Torsion Fatigue Testing Machine.*—To calibrate the repeated-torsion testing machine shown in Fig. 21 a steel bar is clamped to chuck A'', extending at right angles to the axis of the bar D. At the end of this steel bar known weights are hung at a measured distance from the axis of D, and the corresponding readings of the dials M are noted. The readings of twisting moment and dial readings are plotted as a calibration curve from which the twisting moment for any given dial readings can be determined.

24. *Flexure Testing Attachment for Repeated-Torsion Fatigue Testing Machine.*—Figure 23 shows an attachment for the repeated-torsion machine which can be used for testing thin flat specimens in flexure. The specimen S is held at the ends in two vises, V' and V''. V' is mounted in ball bearings so that it is free to turn. V' is at the end of an arm K, fitted with a stub shaft B which is clamped in the jaw A' of the repeated torsion machine. V'' is fitted with a stub shaft C which is clamped in the jaw A'' of the repeated-torsion machine. As the repeated-torsion machine is operated, the specimen S transmits the motion of the head of the jaw A' to the jaw A'', causing cycles of flexure in the specimen S. The range of stress in S during flexure can be adjusted by the screws F (Fig. 21) as in the case of torsion specimens. The bending moment in the critical section of the specimen S is equal to the torsional moment indicated by the dials M multiplied by the ratio y'/y.

Figure 24 shows the bending specimen for use with this bending attachment. This attachment makes it possible to use the repeated torsion machine for the same kind of tests as those made on the flat specimen testing machine shown in Fig. 15.

25. *Advantages and Limitations of Repeated-Torsion Fatigue Testing Machine.*—For a solid torsion specimen, like that shown in Fig. 22, the repeated-torsion machine has the same limitation in the case of stresses beyond the elastic range as do the repeated bending machines previously described. If a hollow specimen with thin walls is used, this limitation may be largely overcome, since the shearing stress in such a specimen is very nearly uniformly distributed. However, such a specimen would be decidedly more expensive to machine than would a solid specimen.

In the case of the bending attachment for the repeated-torsion machine the advantages and limitations are about the same as those for the flat specimen testing machine shown in Fig. 15. It is possible to vary the range of stress in this bending attachment by varying the position of the screws F in Fig. 21. However, it must be noted that if on one side of the specimen the tensile stress is increased and the compressive stress decreased by this adjustment, that on the other side the tensile stress will be decreased and the compressive stress will be increased.

V. Other Types of Fatigue Testing Machines

26. *Alternating-Current Magnet Type and Inertia Type Fatigue Testing Machines.*—Two types of fatigue testing machines which have not been described in this circular are (1) the alternating current magnet type, and (2) the inertia type. In the alternating current magnet type repeated stress is set up by the action of an alternating current. The Haigh machine is the best known example of this type, and it uses the alternating effect of a pair of magnets, each of which is connected to one phase of a two-phase alternating current circuit. It is necessary with the alternating current magnet type of machine to "tune" the vibrating system, including the specimen, to the variations of the circuit by means of adjustable masses of metal, or by adjustable springs. This type of machine in skillful hands can give excellent results, and can develop very high speeds. It is, however, very expensive. At the University of Illinois the variation in frequency of the alternating current supplied to the laboratory made its reliability doubtful.

The same limitation has worked against the adoption at the University of Illinois of the inertia machine. This type of machine sets up cycles of stress either by the reciprocating motion of a mass of metal, or by the varying direction of centrifugal force in a rotating eccentric mass of metal. Where very precise constancy of speed can be depended on, the inertia type of machine may be found very useful.

VI. Surface Finish of Specimens for Fatigue Tests

27. *Surface Polish of Fatigue Specimens.*—Especially in the case of very strong steel, or very brittle metal, the surface polish of fatigue specimens may produce an appreciable effect on the fatigue strength developed. For all flexural and tension-compression specimens a longitudinal polish is preferable to a transverse polish, because very fine scratches in the longitudinal direction do not set up such effective localized stresses as do transverse scratches. In the case of flat specimens longitudinal polish is as easily applied as transverse. In the case of round specimens a longitudinal polish may be applied by rotating the specimen very slowly while the polishing paper is rapidly rubbed back and forth longitudinally.

In the case of torsion specimens either circumferential or longitudinal polish makes the fine scratches run across one direction of shearing stress, so that there is no particular advantage in either method of polishing.

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